



# Current Research Activities in Drive System Technology in Support of the NASA Rotorcraft Program

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## Abstract

Drive system technology is a key area for improving rotorcraft performance, noise/vibration reduction, and reducing operational and manufacturing costs. An overview of current research areas that support the NASA Rotorcraft Program will be provided. Work in drive system technology is mainly focused within three research areas: advanced components, thermal behavior/emergency lubrication system operation, and diagnostics/prognostics (also known as Health and Usage Monitoring Systems (HUMS)). Current research activities in each of these activities will be presented. Also, an overview of the conceptual drive system requirements and possible arrangements for the Heavy Lift Rotorcraft program will be reviewed.

## Introduction

Drive system technology is a very important part of a rotorcraft's design. The design choices that are made can have a drastic impact on the weight, performance, reliability, and cost. Research in the drive system area can have a dramatic affect on these very important design parameters. Basic research is the first step to having drive system improvements make their way into the products. These improvements are being developed through a combination of analytical model development, experimental component tests, and system validation.

There has been an on-going research program of mechanical component technology that has been in existence for over 30 years at NASA Glenn Research Center. The focus of current programs consists of three principal areas. These three areas include advanced components, thermal behavior of gear systems/loss-of-lubrication technology, and health and usage monitoring (HUMS) of mechanical components.

An overview of current test facilities used for validation at the component and system levels is shown in figure 1. Test facilities are used for detailed experimentation of single components or a system of components up to a full

helicopter main rotor transmission. Some of the current uses of the test facilities include contact and bending fatigue of gears, assessment of drive system performance and thermal behavior, and failure progression testing of gears and bearings. Use of these facilities is essential in providing validation for empirically and analytically developed assessments of gear performance, life, etc.

An overview of the current analytical techniques developed by or for these efforts is shown in figure 2. Analytical tools include specialty finite element analysis tools for analysis of mechanical components such as gear bending stress during meshing, dynamic analysis of systems, multi-body contact of gearing members such as in a planetary gear train, and combined fracture analysis combined with gear geometry. The objective of this paper is to summarize the current drive system technologies being developed at NASA Glenn Research Center that support the ongoing rotorcraft effort.

## Advanced Components

Advanced component technology development is currently being assessed in several test projects. Face gear technology is being developed for helicopter main rotor transmissions. Formate gear manufacturing to replace the more expensive spiral bevel generated gearing is being investigated as a cost reduction method for rotorcraft. Ultra high cycle bending fatigue of gears is being investigated to ensure that systems required to operate for billions of stress cycles will be successful without failure. Finally on a more advanced combination of gearing systems, several candidate systems that can have a high gear ratio in one stage are being assessed. High gear ratio can have a large impact on drive system weight as fewer stages may be needed to attain the same gear ratio required from the high speed gas turbine engine speed to that of the main rotor of the helicopter.

**Face gear technology.**—A test program has been under way at NASA Glenn since the early 1990's to investigate the feasibility of using face gears in a main rotor transmission for rotorcraft (refs. 1 to 3). This activity

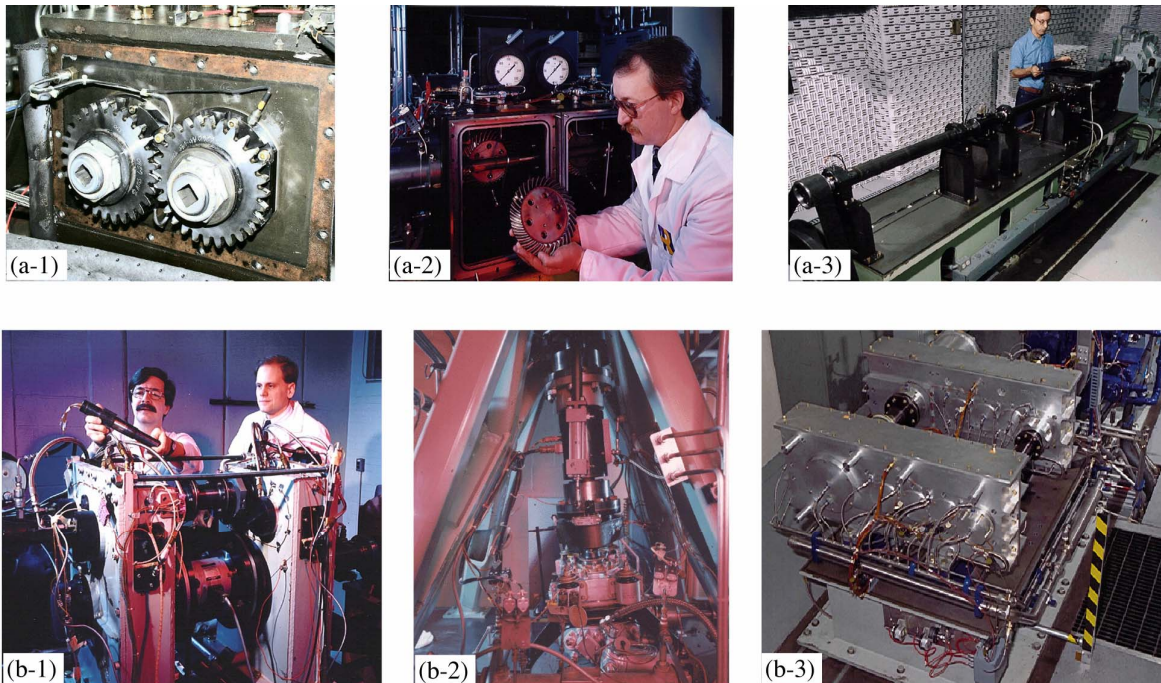


Figure 1.— Overview of test rigs. (a-1) Spur Gear Fatigue Test Rigs. (a-2) Spiral Bevel Fatigue Test Facilities. (a-3) Gear Noise/Dynamics Test Facility. (b-1) Split Torque Test Facility. (b-2) OH-58 Transmission Test Facility. (b-3) High Speed Helical Gear Train Test Facility.

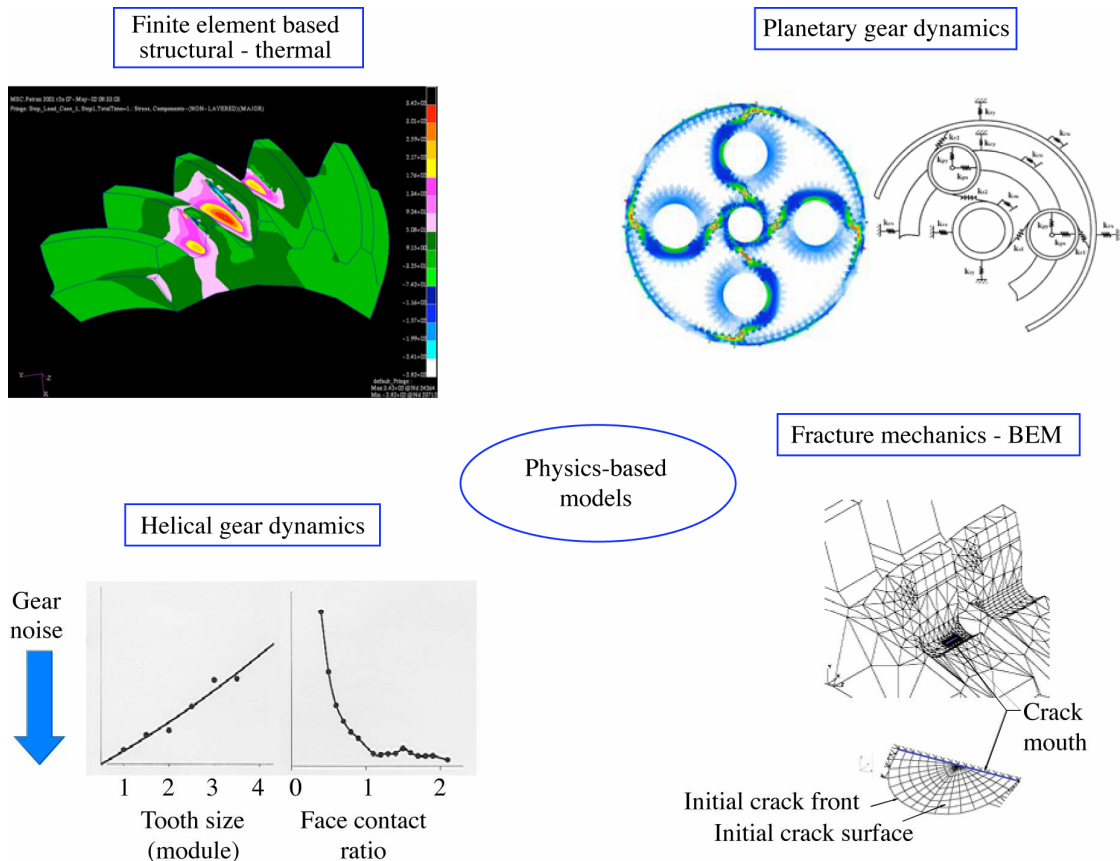


Figure 2.— Overview of analytical capabilities.

has evolved from the basic study of their operational characteristics to that of having precision gears manufactured to high quality levels comparable to other gear types. There has also been a complimentary gear geometry improvement-manufacturing method development (refs. 4 to 6) that has aided in the success of face gears and future use in main rotor transmissions for helicopters. This type of gear system is illustrated in figure 3. The purpose of this type of gear is to turn the corner from the horizontal gas turbine engine to the near vertical rotor shaft. In particular face gears can have a substantial weight benefit by being able to split power and thus reducing the load required to be carried by any of the components essentially in half. An example of how this might be done is shown in figure 4.

The current activity is investigating the fatigue behavior of the gear mesh type in the NASA Spiral Bevel/Face Gear Test Facility. Two sketches are shown in figure 5. Part (a) shows the overview of the facility and part (b) shows a cross-sectional view of the facility configured to test face gears.

**Formate gear technology.**—The use of spiral bevel gears to turn the corner between the engines and rotor shafts, as mentioned above, is currently done on all U.S. made rotorcraft. The manufacture of these components requires special machine tools entirely dedicated to their efficient and accurate manufacture (fig. 6). This

manufacturing process is tied to coordinate measuring machinery so that gear geometry and accuracy is maintained. Spiral bevel gears made for rotorcraft are individual part numbers and not matched sets as done in some other intersecting axis gearing (such as used in rear wheel drive automobiles, trucks, etc.). Therefore, the pinion and gear for a given design can be assembled and function as intended. Several recent projects have investigated the various effects of gear geometry changes in an actual rotorcraft transmission. These projects have shown that very subtle changes in gear geometry can have a substantial impact on the load carrying ability, noise level, and vibration level of the transmission system (refs. 7 to 9).



Figure 3.—Face gear drawing showing pinion and gear (ref. 4).

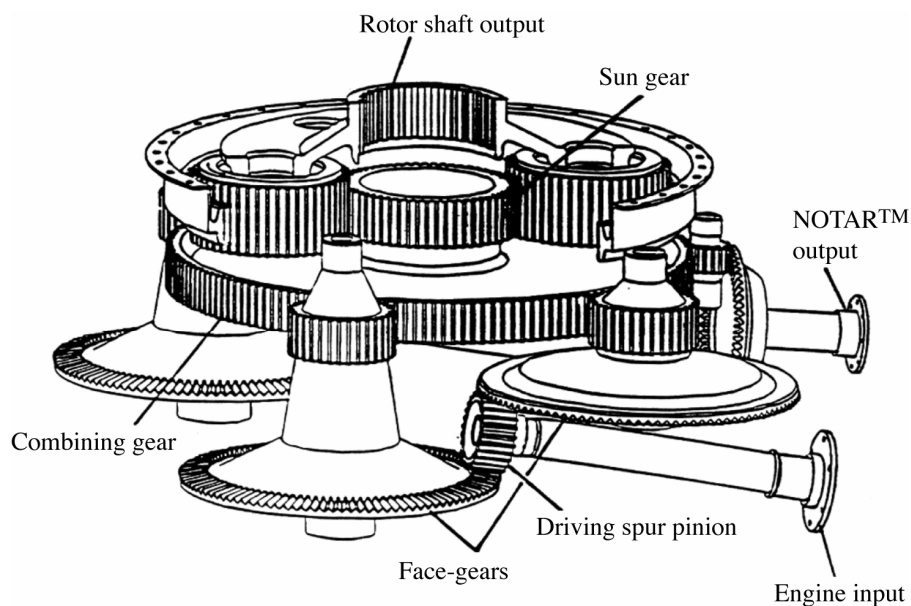
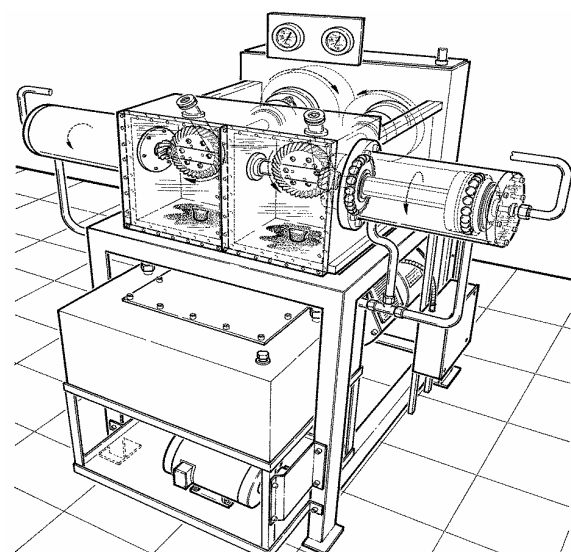
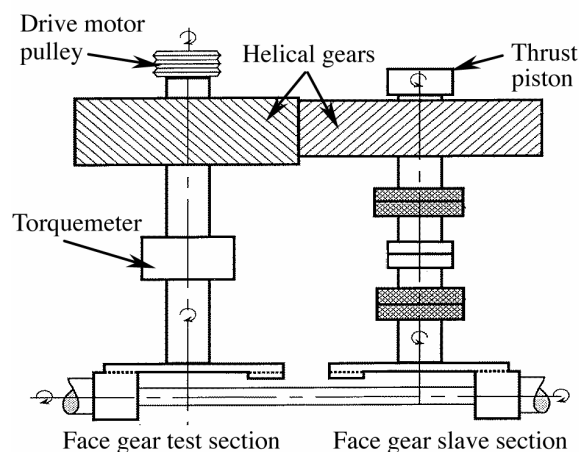


Figure 4.—Face gear split torque use in rotorcraft transmissions.





(a)



(b)

Figure 5.—Spiral bevel/face gear test rig. (a) Overview of facility. (b) Schematic view.

The difference between spiral bevel and Formate gears is in the manufacture of the gear member. Typically the gear ratio used for this gear mesh in rotorcraft is 4:1 or greater, meaning there are four times as many teeth or it takes four times as long to manufacture. In both cases the pinions are manufactured using a generating motion that requires considerable manufacturing time. In the case of spiral bevel gears, the gear is also made using this process. Therefore, the benefit of using the Formate type of gear system is that the gear is not manufactured using a generating motion. Instead, the tool is fixed in its setting and the gear being cut is fed directly into the tool without relative motion needed for the pinion. This subtle difference substantially reduces the time needed for manufacture.

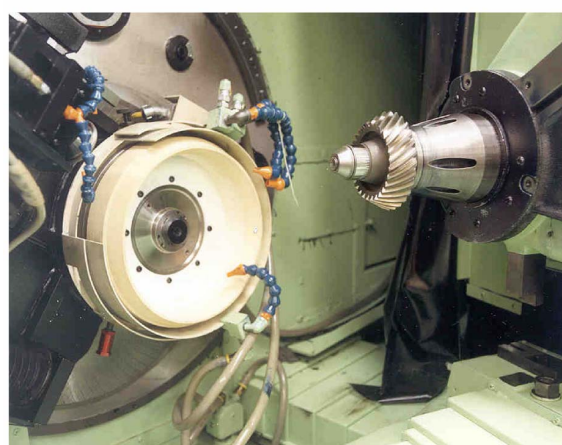


Figure 6.—Machine tool used for spiral bevel gear production.

In an effort to substantiate the benefits, test hardware has been manufactured and is currently being prepared for testing. Tests will be conducted in the NASA Glenn Research Center's OH-58 Helicopter Transmission Test Stand (fig. 7). Testing will be done to investigate the noise, vibration, and bending stress changes as compared to the generated baseline test hardware that was accessed in an earlier project.

**Ultra high cycle fatigue.**—Ultra high cycle fatigue behavior of mechanical components is of high importance as expected component lives are in the billions of stress cycles. The current available fatigue data bases known to exist are typically limited to the hundreds of millions of cycles. At this point fatigue at ultra high number of cycles is dealt with by reducing the allowable stress by a factor dependent on the number of expected cycles beyond 10 million cycles (ref. 10).

In an effort to begin to validate the above mentioned procedure an ultra-high bending fatigue facility for gear tooth bending capacity is currently under development.



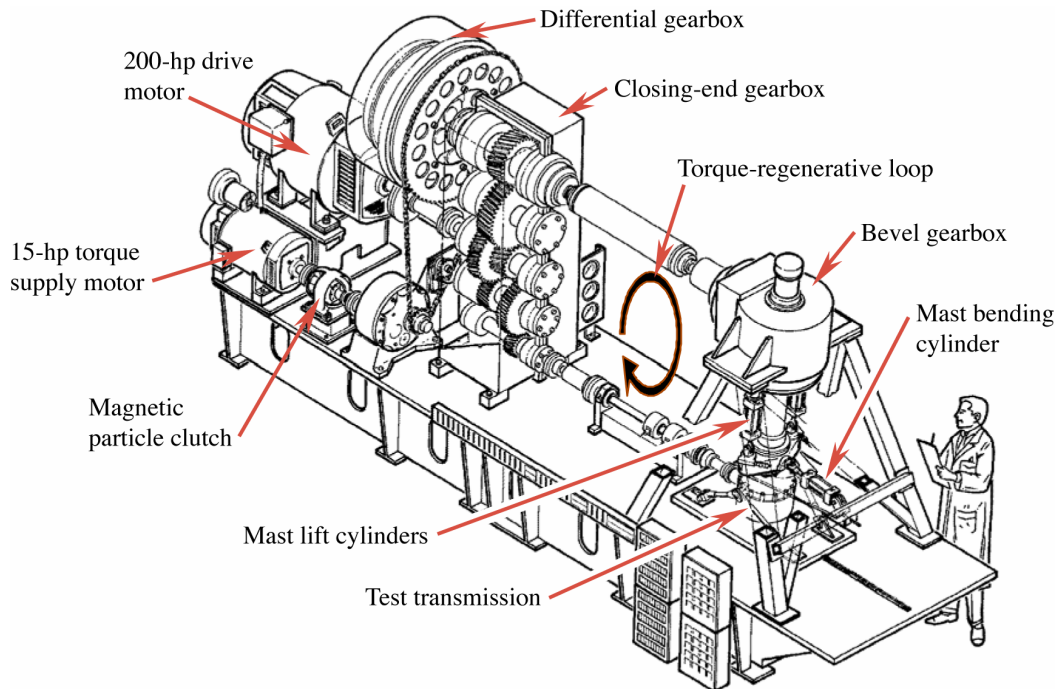


Figure 7.—OH-58 Helicopter Transmission Test Stand.

The test facility is shown in figure 8. A high speed hydraulic system loads the test gear at the highest point of tooth contact (the location that corresponds to the highest bending stress contact position) from some minimal nominal load to the peak force in a sinusoidal manner. The hydraulic systems of similar test equipment typically can operate up to 30 cycles per second. The hydraulic system of the new test facility can operate up to 1000 cycles per second. This high speed condition is similar in loading frequency as if the gear system was rotating at 60,000 rpm. In this manner large number of cycles can be applied in a relatively short time.

**High ratio gearing technology.**—In an effort to fund some out of the box thinking with respect to high-ratio gearing, a grant was funded at the University of Illinois to investigate configurations/systems that could be comprised to reduce the number of gearing stages needed to go from the high speed gas turbine output shafting to the low speed rotor of a helicopter (ref. 11). This effort generated some interesting results with conventional planetary gear systems as well as a configuration using face gears in a concentric shafting arrangement (much like a planetary gear train). One innovative arrangement that was generated is shown in figure 9. Shown in this figure is an input shaft that has a face gear connected to it that meshes with a pinion. The pinion connects via a common shaft to another pinion that meshes with a face gear that does not rotate. The dual pinion shaft is mounted in the “carrier” shaft (the output shaft).

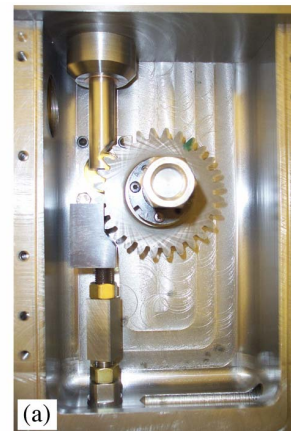


Figure 8.—Ultra-High Bending Fatigue Test Facility.  
(a) Test fixture. (b) Test fixture in fatigue machine.

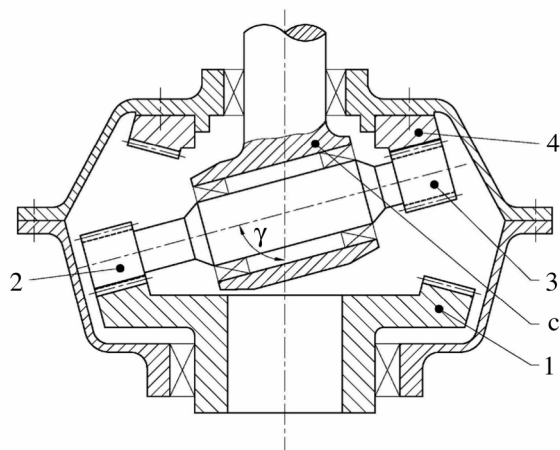


Figure 9.—Face gear planetary configuration (ref. 10).  
(Figure legend: 1 – input face gear, 2 and 3 – power transfer spur gears, 4 – fixed face gear, and c – carrier/output shaft).

For intersecting axis requirements an example of achieving high gear ratio is using face gears. An example of this type of gearing is shown previously in figure 3. With this type of gear mesh at high ratios, the gear set approaches a rack and pinion. With a spur or helical pinion, power splitting is also possible and enhanced power to weight ratio can be achieved.

### Thermal Behavior of High Speed Gearing

**High speed helical gear train.**—As engine speeds increase, the need for efficient high speed gearing becomes more important. At high rotational speed (pitch line velocity) the losses from the gear train windage can become a dominant portion of the gearing losses or efficiency reduction. An understanding on how certain operational, design, and configuration can affect the performance is very important. Also and certainly as important are how these high speed gear systems operate in the loss-of-lubrication mode. All helicopters are required to pass a 30 min loss of primary lubrication for a scripted flight. This test is typically done after all other qualification requirements are met. Failure of the system at this point can lead to expensive redesign, modifications, and ultimately another loss of lubrication system test. Both the normal and loss-of-lubrication operational modes are of great importance to the main rotor transmissions of rotorcraft.

The High Speed Helical Gear Train Test Facility at NASA Glenn Research Center is used to investigate the thermal behavior of full scale flight test hardware. An artist's sketch of the facility is shown in figure 10 and the actual test hardware is shown in figure 11. The test facility can operate at conditions up to 15000 rpm and 5000 hp. In this full scale test many system operational parameters as

well as design arrangements can be tested. Examples of some data taken during recent testing (refs. 12 and 13) are shown in figure 12. In these graphs, the effects of lubricant jet pressure and gear shrouding are shown as a function of input shaft speed. The important parameter of the testing, shaft speed, can dominate the results over other parametric changes.

**Vapor/mist lubrication.**—For the emergency (loss-of-lubrication) conditions, simpler component tests are conducted to try to come up with improved lubricants and application technologies (refs. 14 and 15). These techniques will enhance the operational behavior under these very difficult environmental conditions. The test facility used for this type of testing is shown in figure 13. Typically this facility is used to conduct surface fatigue experiments. Some recent and promising test results are shown in figure 14. In part (a) of this figure a test conducted using misted synthetic, ester based, hydrocarbon lubricant resulted in high surface wear after 9 million cycles. In figure 14 (b), an enhanced lubricant, a synthetic thioether, using the same vapor/misting technique resulted in very little wear with minimal temperature increase (no coking of the lubricant on the meshing gear surfaces). The testing that has been described is necessary prior to demonstration in a larger full scale test of flight relevant components.

### Health and Usage Monitoring System Technology

**Data Fusion.**—Health and usage monitoring technologies are of great interest at this time as many civil and military applications are trying to move to on-condition maintenance. If this can be accepted as normal operating practice by the authorizing government agencies, then rotorcraft users can benefit from reduced maintenance that is currently dictated from the vehicle's initial qualification.

The other benefit that this technology can provide is from the safety standpoint, as failure of critical components through multiple techniques can be detected in time to complete the mission and schedule required maintenance before problems become catastrophic. Techniques using vibration and oil debris analysis have been under development for some time and common faults such as gear pitting can be detected. Some faults still need additional research and development such as fatigue cracks. This type of failure is difficult to detect early. Also, the mechanical system configuration can have an effect on the ability to detect failures such as in planetary gear trains. In this type of gear stage configuration all the gears (planets, sun, and ring gear) have the same meshing frequency. This means that a flaw on one component can be masked by the others that are operating at the same frequency.

One method to improve the detection capability without having a multitude of false alarms is to use data fusion and make use of several different suites of data to make more informed decision on the health of a particular

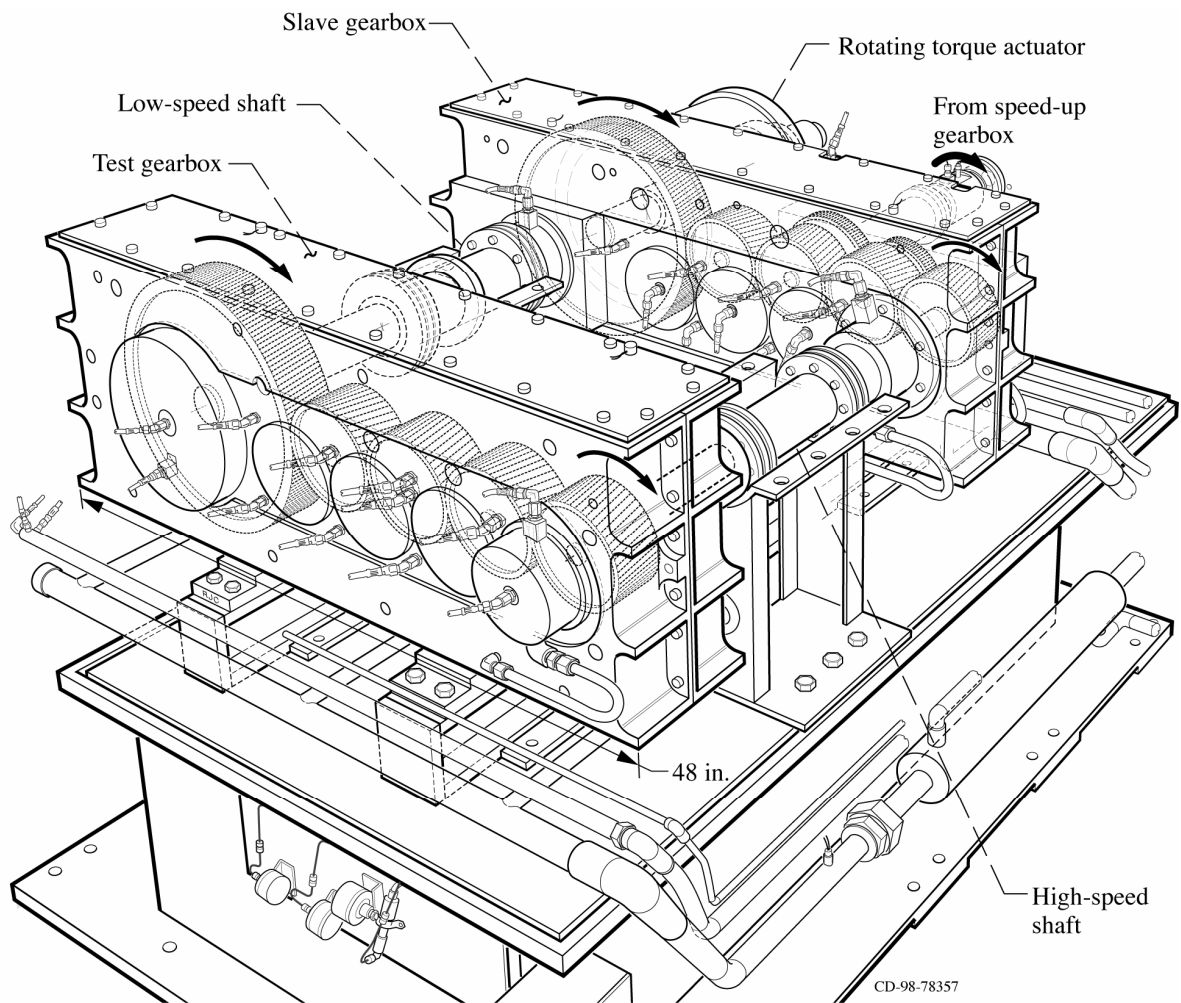


Figure 10.—Sketch of High-Speed Helical Gear Train Test Facility.



Figure 11.—High-speed helical gear train test components.

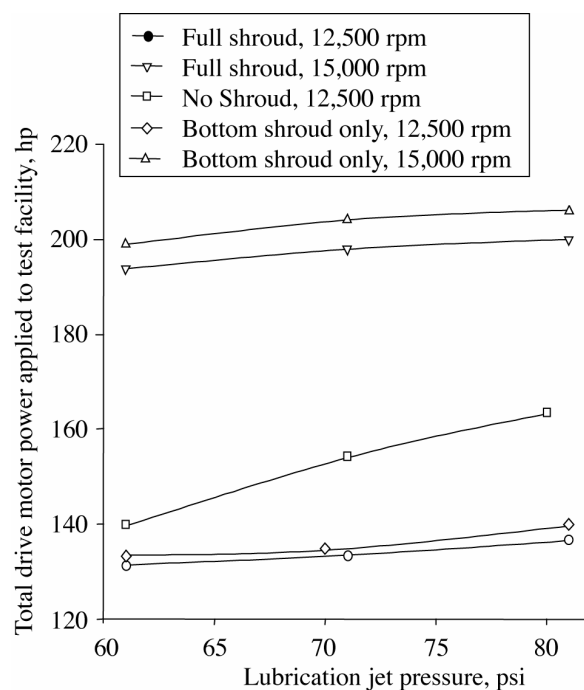


Figure 12.—Example of data taken in the High-Speed Helical Gear Train Test Facility.

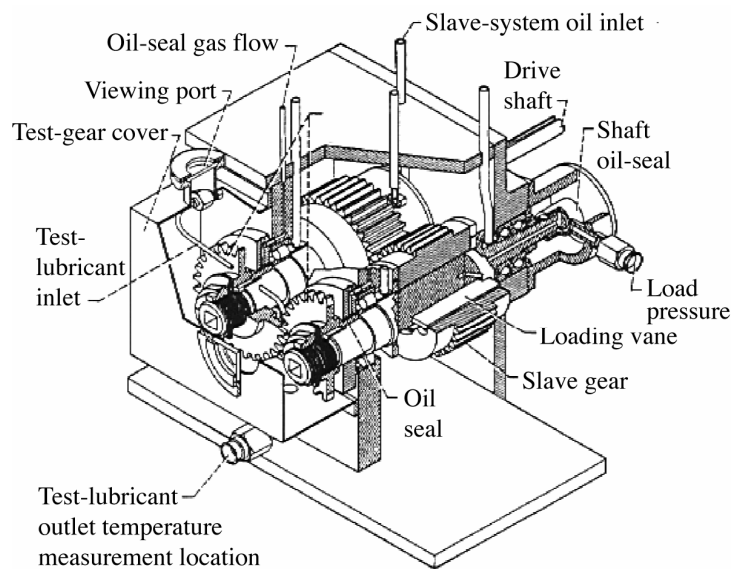


Figure 13.—Spur Gear Fatigue Facility used for loss-of-lubrication studies.



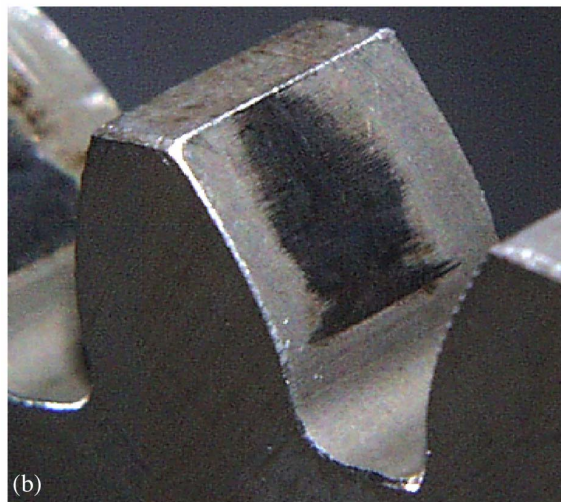
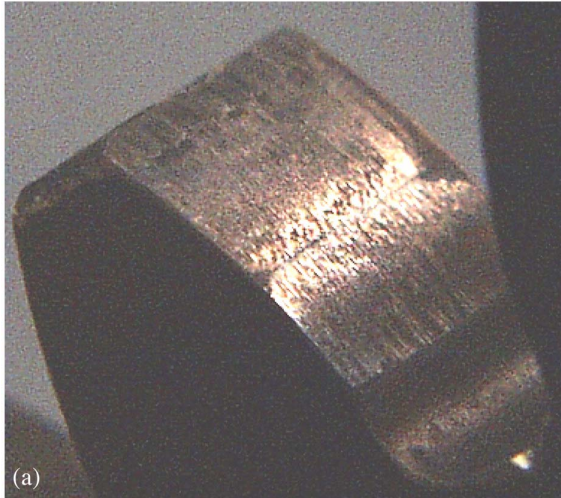
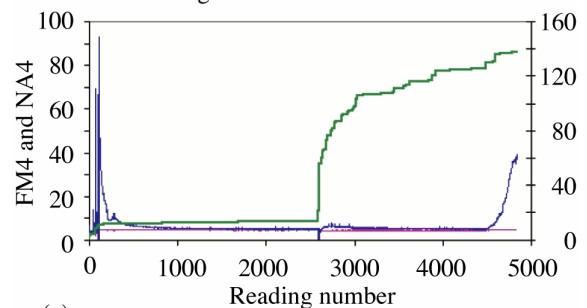


Figure 14.—Results from emergency lubrication system tests.

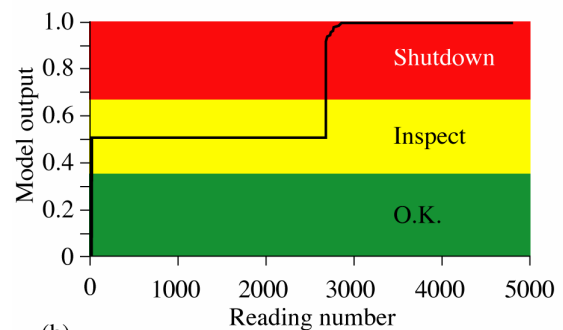
system or component. An example of this is shown in figure 15. In this particular test (a spiral bevel gear fatigue test) some initial pitting of the spiral bevel pinion was indicated (and it arrested itself) and then a facility support bearing spalled (ref. 16). The first indication of a problem was rather early (the pinion pitting) and the second problem was more pronounced (the bearing spall). Vibration and oil debris mass are plotted against reading number in figure 16 (or multiply by 1000 to count the cycles). Also shown in figure 16 is the fused output from the same test. This output indicated the initial pinion spalling as being cause for inspection and more oil debris in the lubricant showed that the system had gone beyond the inspection to the shutdown stage (due to the bearing spalling initiating).



Figure 15.—Spiral bevel gear and bearing that failed during the same test.



(a)



(b)

Figure 16.—Vibration and oil debris data (a) and then processed through a fuzzy logic modeling technique (b).

**Hybrid bearing test facility.**—In all mechanical systems, bearings are important part of the health of a given system. The fatigue failure of bearings (typically high cycle contact fatigue) will generate wear debris as shown in the earlier test (figs. 15 and 16) and will be indicated even on an unsophisticated sensor such as a chip detector. The problem with this type of sensing is that when there are many bearings, how can the problem bearing be found without teardown and inspection. Also, in many future systems the all metallic bearing components will be replaced with ceramic rolling elements. If the rolling element begins to fail without generating metallic race debris, current wear debris detectors will not pick up the progressing failure.

In an effort to investigate how rolling element bearings fail from a health and usage monitoring standpoint, a test facility is under development to help quantify bearing behavior (ref. 17). The facility currently being built is shown in figure 17. In this facility the only rolling element bearing is the test bearing as the supporting shafting within the test fixture uses fluid film bearings. This should make the vibration detection as clean as possible and help establish methods for bearing health.

## Heavy Lift Rotorcraft Propulsion Study

**Introduction.**—As part of the NASA Heavy Lift Rotorcraft study (ref. 18) the propulsion aspects of this vehicle requires significant consideration. The propulsion system for this type of vehicle is considered to be one of

major risk reduction technologies necessary to make the vehicle viable.

As part of the concept phase, many different rotorcraft concepts were developed to meet the mission shown in table 1. Three aircraft were proposed to meet the civil heavy lift mission are the following: (i) tiltrotor, (ii) tandem compound, and (iii) alternating blade concept. One of the key outcomes from these initial studies indicated a need for variable speed propulsion for all three of the concepts that were further studied. Currently all man-rated rotorcraft have fixed ratio in the gear system. This feature is a major departure from current rotorcraft drive system requirements.

Rotorcraft design codes were used to attain the propulsion system requirement shown in table 2. Notice that in table 2 each propulsion system rotors/propellers/propulsors change speed between hover and forward flight (cruise). This need for variable speed must either be accomplished via the engines, the drive system, or a combination of both. Note that each aircraft required four engines and total power required ranged from 28000 to 52000 hp.

As part of the activity, drive system arrangements were proposed as a starting point to laying out the gearing arrangements necessary to connect the engines to the rotors, propellers, and propulsors. At this point it was assumed that engine speed variation was not required to achieve the speed changes that each vehicle requires. If engine speed variation can be achieved without severe performance

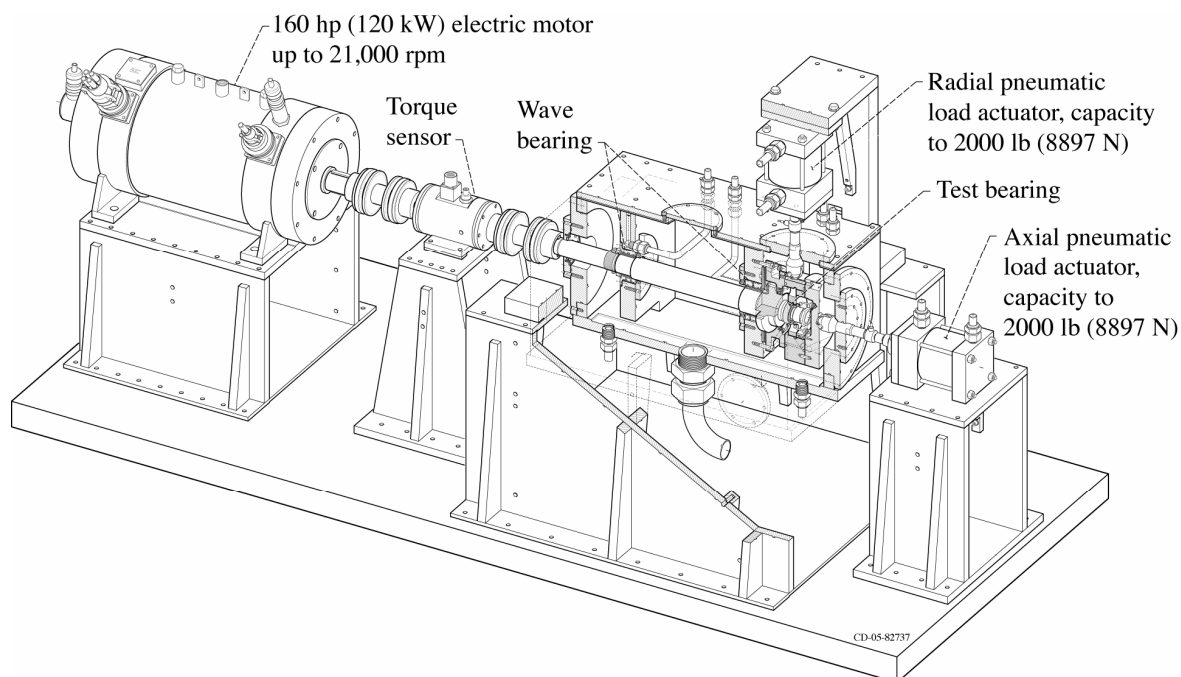


Figure 17.—Bearing Diagnostic Test Facility.



TABLE 1.—NASA CIVIL HEAVY LIFT  
ROTORCRAFT REQUIREMENTS

ROTORCRAFT NOTION VEHICLE 15-YEAR CAPABILITIES	
Payload	120 passengers
Cruise speed	M = 0.60 (350 knots) at 30000 ft
Cruise altitude	at or above 22000 ft (icing)
Range	1200 nm
Operations	Automated single-pilot CAT IIIC SNI for heavy lift
Hover efficiency, W/P	6
Efficient Cruise, L/D	12
Empty Weight Fraction	0.41
Community Noise	SOA-14 EPNdb
Flight Control	Automated single-pilot CAT IIIC SNI for heavy lift
Advanced Engine SFC	SOA-10%
Advanced Engine SHP/W	SOA*120%
Cabin Noise and Vibration	77dBA and 0.5 g

TABLE 2.—BASIC PROPULSION REQUIREMENTS

	Large Civil Tilt Rotor	Large Civil Tandem Compound	Large Advancing Blade Concept
Vehicle Gross Weight, lbs	123,257	134,109	150,537
Engine, shp	7,007	9,700	12,979
Engine, rpm	18,394	16,159	14,444
Number of Engines	4	4	4
Total Power Available	28,028	38,800	51,916
Hover, rpm	140	165	147.3
Cruise, rpm	75.5	51.9	57.6
Propeller, rpm		573.0	477.5

benefits, then the drive system gear ratio reduction requirements would be less and the possible need for a mechanical system speed change mechanism might be eliminated. Possible gas turbine engine system enhancements for variable speed were considered in the work contained in (ref. 19). Many different concepts were proposed with the lowest risk technology to achieve variable speed used turbine blades that can tolerate flow incidence angle changes without major performance

degradation. This method of varying speed requires a separate engine technology developed and validation program that is directly applicable to the turbo-shaft engines needed for the heavy lift rotorcraft concepts under consideration.

Assuming that the drive system requires variable speed capability, the most beneficial place to locate this device would be at the highest shaft speed/lowest torque location. Having the variable speed device at this location will result in the lowest weight penalty for the device. At this point no possible aerospace solutions will be proposed, but many possible arrangements have been documented in (refs. 20 and 21).

The conceptual drive system arrangements for each aircraft will now be presented. In figure 18 the drive system arrangement for the tiltrotor is shown. A variable speed/combiner gearbox would be necessary to bring the two engines together at the highest shaft speed location. At the exit of the combiner gearbox would be a bevel gear arrangements that could send power two directions. One bevel gear output would be sent to the reduction gearbox that turns the propeller and the other would go to the mid-wing gearbox as utilized in other tiltrotor aircraft. The reduction gearbox would have an input bevel gear mesh that then transfer's power through a two stage planetary prior to turning the propeller/rotor. The cross shafting and mid-wing gearbox provide one engine inoperative capability.

For the tandem compound drive system variable speed capability is necessary in two locations (fig. 19). One would be at the engine combiner stage and one at the propeller gearbox. A gearbox at the mid-wing location would be necessary to distribute power to the forward and aft main rotor gearboxes. Once again the two gas turbine engines need their power shafts connected and then sent multiple directions. In this configuration the power needs to go to the propeller and to the combiner gearbox. In forward flight the main rotors are not required to aid in the propulsion and only provide lift. In the hover condition the rotors must deliver all the lift.

For the advancing blade concept the drive system has many of the attributes already discussed above plus the need for counter-rotation of the main rotors. A possible configuration for this design is shown in figure 20. Variable speed gearboxes are required for each engine as well as the propulsor that is at the aft end of the and need to be slowed as the aft propulsor provides the necessary forward thrust for cruise conditions.

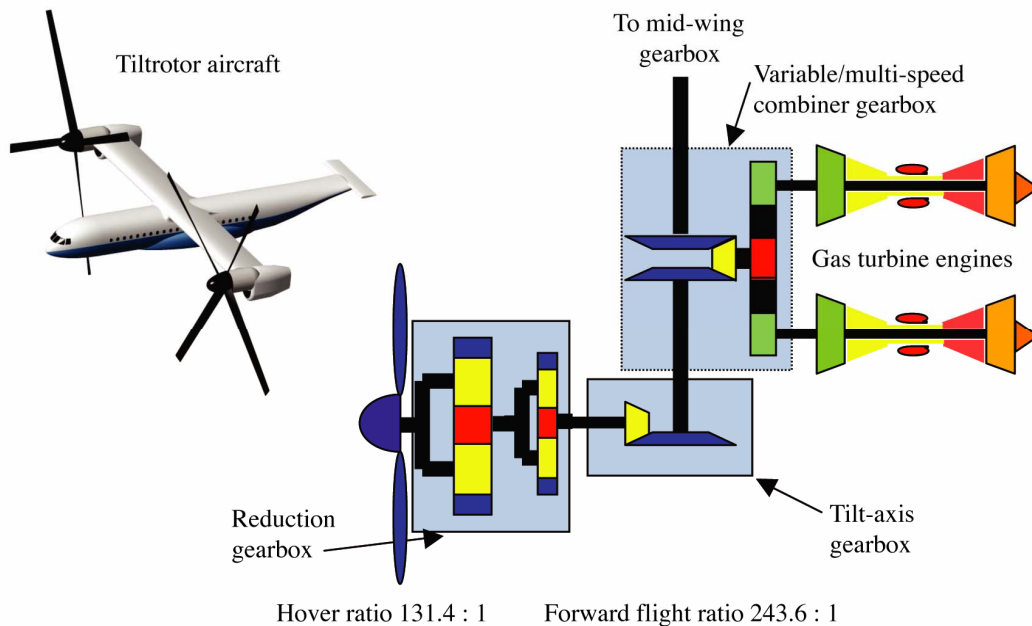


Figure 18.—Proposed drive system arrangement for the Heavy Lift Civil Tiltrotor.

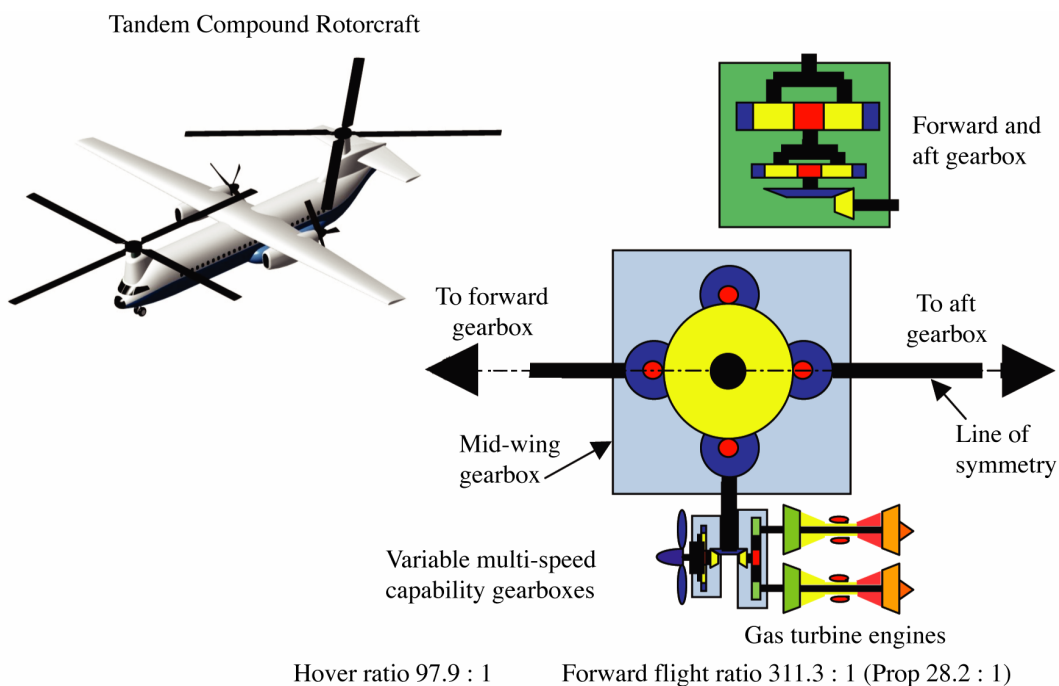


Figure 19.—Proposed drive system arrangement for the Heavy Lift Tandem Compound Rotorcraft.

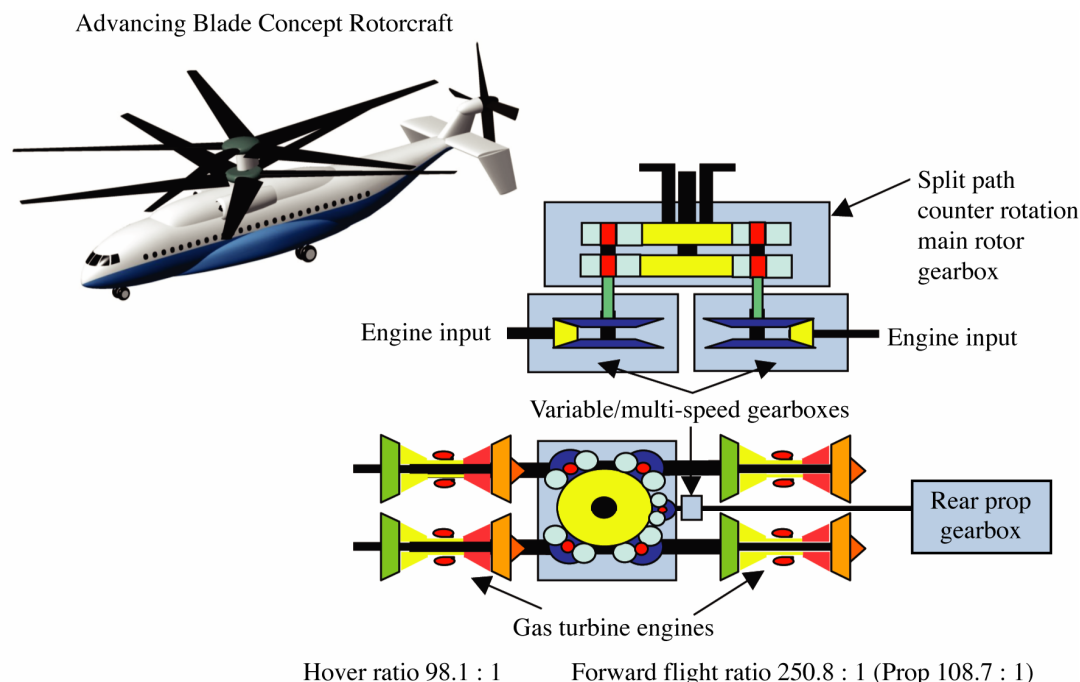


Figure 20.—Proposed drive system arrangement for the Civil Heavy Lift Advancing Blade Concept Rotorcraft.

Some possible drive system arrangements have been proposed assuming that variable speed aspects will be developed. When a variable speed mechanism is designed into a rotorcraft, the system must have the capability to fail without compromising the operation of the rotorcraft. Also, there needs to be careful consideration given to control of the rotors and propellers to provide a comfortable and efficient transition between the various flight modes.

## Summary

In summary, current research activities within NASA Glenn Research Center's Mechanical Components Branch support improvements in technologies that affect performance, noise, vibration, safety, and reliability. The programs being worked on fall into three basic categories; (1) advance component research, (2) thermal behavior of high speed mechanical systems that includes normal and emergency lubrication operational conditions, and (3) diagnostics/prognostics technologies. Improvements in these three critical areas of research can have an effect on the overall rotorcraft systems of current and future aircraft.

Also, an effort was undertaken to generate possible propulsion arrangements for a civilian heavy lift rotorcraft. Three different aircraft configurations required three different possible drive system arrangements. From the rotorcraft sizing analysis effort for the mission assumed, all three heavy lift rotorcraft also required variable speed propulsion. In this study possible drive system

arrangements were proposed for the non-variable speed part of the drive system. An extensive research programs will be necessary to investigate variable speed technologies that could be developed for drive system and gas turbine engines to efficiently transition through various flight regimes.

## References

1. Heath, G., and Bossler, R.: Advanced Rotorcraft Transmission (ART) Program—Final Report, NASA/CR-191057, ARL-CR-14, January 1993.
2. Handschuh, R., Lewicki, D., and Bossler, R.: "Experimental Testing of Prototype Face Gears for Helicopter Transmissions," Proc. of Institute of Mechanical Engineering, Vol. 208, 1994.
3. Lewicki, D., Handschuh, R., Heath, G. and Sheth, V.: Evaluation of Carburized and Ground Face Gears, Journal of the American Helicopter Society, Vol. 45, No. 2, pp. 118–124, April, 2000.
4. Litvin, F., Fuentes, A., Zanzi, C., and M. Pontiggia, M.: Face Gear Drive With Spur Involute Pinion: Geometry, Generation by a Worm, Stress Analysis, NASA/CR—2002-211362, ARL-CR-491, February, 2002.
5. Litvin, F., Nava, A., Fan, Q. and Fuentes, A.: New Geometry of Worm Face Gear Drives With Conical and Cylindrical Worms: Generation, Simulation of

- Meshing, and Stress Analysis, NASA/CR—2002-211895, ARL—CR—0511, November, 2002.
6. Litvin, F., Fuentes, A., Gonzalez-Perez, I., Piscopo, A. and Ruzziconi, P.: Face Gear Drive With Helical Involute Pinion: Geometry, Generation by a Shaper and a Worm, Avoidance of Singularities and Stress Analysis, NASA/CR—2005-213443, ARL—CR—557, February 2005.
7. Lewicki, D., Handschuh, R., Henry, Z., and Litvin, F.: Low-Noise, High-Strength, Spiral Bevel Gears for Helicopter Transmissions, AIAA Journal of Propulsion and Power, Vol. 10, No. 3, pp. 356–361, 1994.
8. Litvin, F., Zhang, Y., and Handschuh, R.: Computerized Design of Low-Noise Face-Milled Spiral Bevel Gears, NASA/TM—106713, ARL—TR—306, September 1994.
9. Lewicki, D., Handschuh, R., Henry, Z., and Litvin, F.: Improvements in Spiral Bevel Gears to Reduce Noise and Increase Strength, NASA/TM—106613, ARL—TR—459, September 1994.
10. AMSI/AMGA 2001-C95, Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth, American Gear Manufacturers Association, Alexandria, VA, October 1994.
11. Litvin, F., Fuentes, A., Vecchiato, D., and Gonzalez-Perez, I.: New Design and Improvement of Planetary Gear Trains, NASA/CR—2004-213101, ARL—CR—540, July 2004.
12. Handschuh, R., and Kilmain, C.: Efficiency of High-Speed Helical Gear Trains, NASA/TM—2003-212222, ARL—TR—2968, April 2003.
13. Handschuh, R. and Kilmain, C.: Experimental Study of the Influence of Speed and Load on Thermal Behavior of High-Speed Helical Gear Trains, NASA/TM—2005-213632, ARL—TR—3488, July 2005.
14. Handschuh, R., and Morales, W.: Lubrication System Failure Baseline Testing on an Aerospace Quality Gear Mesh, NASA/TM—2000-209954, ARL—TR—2214, May 2000.
15. Morales, W. and Handschuh, R.: A Preliminary Study on the Vapor/Mist Lubrication of a Spur Gearbox, STLE Jour. of Lubrication Engineering, Vol. 56, No. 9, pp. 14–19, 2000.
16. Dempsey, P., Handschuh, R., and Afjeh, A.: Spiral Bevel Gear Damage Detection Using Decision Fusion Analysis, NASA/TM—2002-211814, ARL—TR—2744, August 2001.
17. Dempsey, P., Certo, J., Handschuh, R., and Dimofte, F.: Hybrid Bearing Prognostic Test Rig, NASA/TM—2005-211814, ARL—TR—3454, August 2005.
18. Johnson, W.; Yamauchi, G.K.; and Watts, M.E. “NASA Heavy Lift Rotorcraft Systems Investigation.” NASA/TP—2005-213467 (to be published).
19. D’Angelo, M.: Wide Speed Range Turboshift Study, NASA/CR-198380, August 1995.
20. Bossler, R.: Vertical Lift Drive Systems Concepts Studies, NASA/CR—2002-211563, ARL—CR—496, June 2002.
21. Kish, J.: Vertical Lift Drive System Concept Studies, Variable Speed/Tow-Speed Transmissions, NASA/CR—2002-211564, ARL—CR—495, June 2002.

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